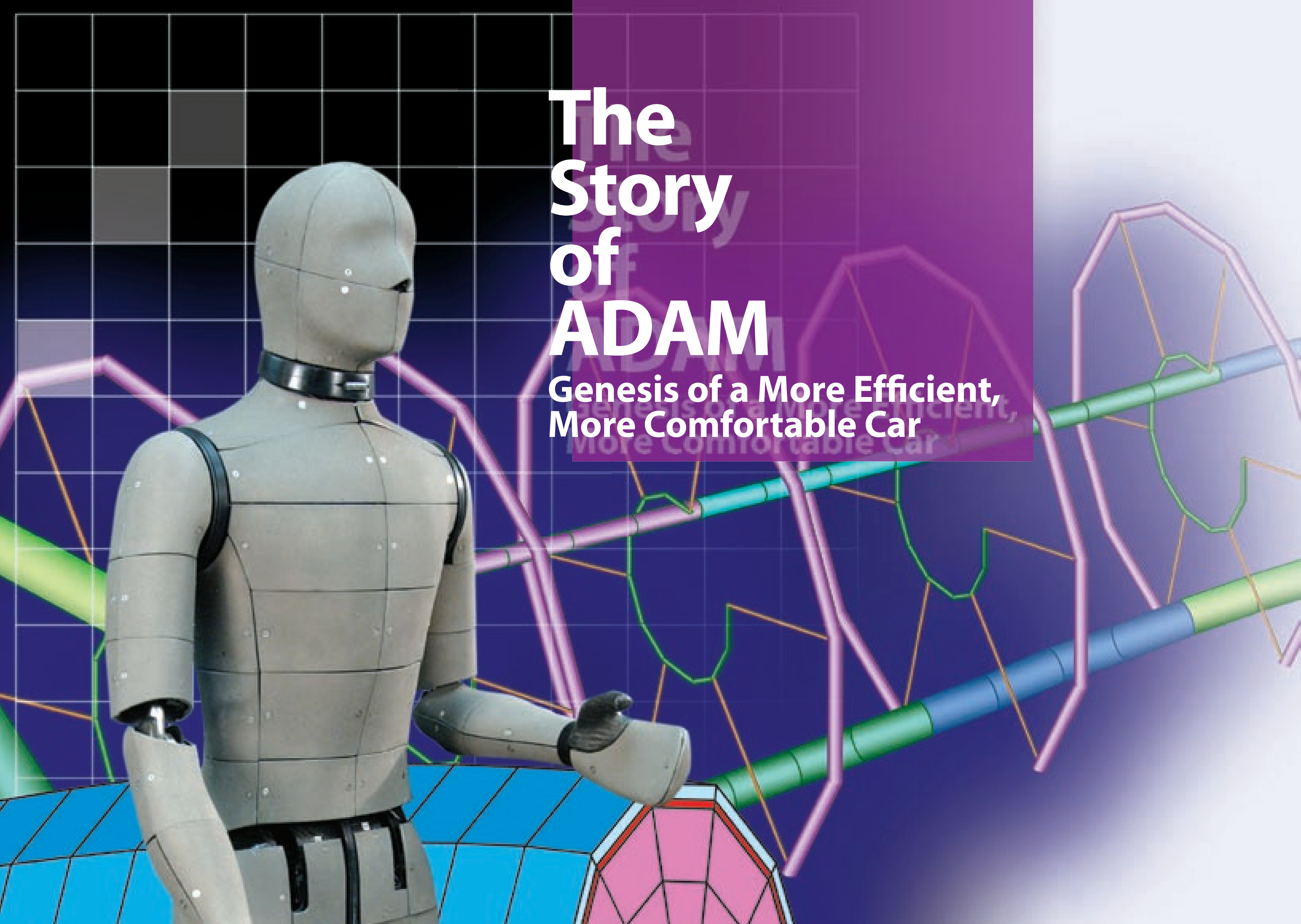


The Story of ADAM

Genesis of a More Efficient, More Comfortable Car

In America, the personal car (or light truck) is not only a right we expect, or a necessity for our way of life but also a symbol of our freedom. So with the twin threats of rising energy prices and increasing worldwide tailpipe emissions, are we in danger of tarnishing or losing our symbol? No. With the potential of new materials and upcoming technologies, we may be re-inventing the car and the freedom it represents.

The next generation of vehicles, for example, will bring a greater freedom of choice. We will be able to select the chassis we want and the body type to fit on that chassis; or even several body types to fit a single chassis.

It will bring the freedom of new materials out of which to make car bodies—new fibers or composites that weigh far less than today's materials, are stronger, longer-lasting, do not rust, can better stand impacts, and provide greater safety. The new materials also will bring a new way to manufacture cars. Car bodies could be molded and stamped out, in contrast to meticulously riveting and welding them together. This, in turn, will bring greater liberty to design car bodies.

The next generation of cars will also provide greater energy and environmental freedom. We will, for example, see a dramatic rise in the use of HEVs (hybrid electric vehicles) in which an internal combustion engine (ICE) is used in combination with batteries, an electric motor, and generator to power our cars. Today, HEVs are some of the most fuel-efficient vehicles on the road, and the concept is starting to be offered not just in compact cars but also in luxury cars, SUVs, and other vehicles. The components that constitute a car's propulsion system will become more compact, efficient, and lightweight. Vehicles will get double or triple their fuel economy and greatly increase their range.

We will also see the beginning of the hydrogen economy, in which hydrogen will be used to power our vehicles, using fuel-cell technology. Fuel cells are not only far more efficient than ICEs, but they produce no pollution or greenhouse gases—the only product of a hydrogen fuel cell (other than energy) is water vapor.

Our next generation of cars will be sleeker and more comfortable. The hump that runs down the middle of the floors of many cars could become an historical curiosity, as could foot pedals and mechanical devices used to control our cars.

And they will have A/C (air conditioning) components, systems, and strategies that will make you more comfortable on a hot day and do it more efficiently, saving considerable energy.

ADAM—Helping to Design Efficient Ancillary Systems

This is where ADAM (NREL's ADvanced Automotive Manikin) comes in, to help us design systems and strategies to make you more comfortable in your car. ADAM may be a manikin, but he's more than a crash-test dummy.

Crash-test dummies are made of materials to simulate humans during crash tests. They have sensors in the head, neck, legs, torso, and feet that collect and relay information about results of the crash tests—acceleration and deceleration, forces on different parts of the body, and the deflection of parts of the body during a crash. This information has helped auto makers design and build cars that are far safer than those of decades ago. Today, you would be hard put to find a new car without seat belts, air bags, a collapsible steering column, and more, all as standard features.

ADAM is analogous to crash-test dummies except that he breathes, heats, sweats, and tells us how comfortable he is. But we don't crash him into walls or ram things into him. Rather, we put him into hot (or cold) cars to see how he feels and to see how we can make him comfortable. ADAM will do for efficiency and comfort what crash-test dummies did for automobile safety. The information he generates will help us design cars that will cut the energy a car uses for ancillary loads—like climate control, power steering, lighting, water and oil pumping, all of which require fuel but are not used to propel the vehicle.

When operating, the most energy-intensive of these is the A/C load. To see why, consider that your body generates 100–150 W of heat. But to cool you down, your car uses up to 6,000 W of power. This is because the A/C system is designed not simply to cool you, but also to cool the entire car for the worst-case scenario—in Phoenix, Arizona, in the height of summer after the car has been soaking in the hot sun.

Using this kind of vehicle-cooling strategy, the United States today consumes about 7 billion gallons of gasoline per year just to cool its cars. This is equivalent to nearly 10% of the oil we import, which costs the nation about $13 billion per year. It also adds considerably to air pollution, increasing the tailpipe emissions of nitrogen oxides, carbon monoxide, and hydrocarbons.

This need not be. We can cool our cars far more efficiently, more quickly, less expensively, using far less fuel, and be more comfortable in the bargain. To accomplish this, we have to design new components and systems and test the results of incorporating them into our vehicles. But to test a wide variety of people with different comfort zones and in different conditions would be time-consuming and expensive. This is where ADAM comes in, as a surrogate for this testing, which will help streamline the process for design and implementation.

Three-Part Harmony

To be a reliable proxy for how we sense and respond to heat and cold and how comfortable we feel, ADAM the manikin cannot stand alone. Rather, he is simply the physical, sensing component of a three-part system that also has a regulatory component (a physiological-response model), and a feeling component (a thermal-comfort model).

ADAM the Sensor. As a manikin, ADAM can sense and respond to the environment, but his response is directed and controlled by the physiological response model. ADAM is designed to represent the 50th percentile American male. He is 5 ft. 9 in. tall (175 cm) and weighs about 136 lbs. (61 kg). He is flexible at the waist, and has adjustable pre-tensioned joints at the knees, feet, wrists, elbows, and shoulders that allow him to be posed in various positions, most notably sitting behind the steering wheel of a car.

ADAM has two major layers—a skeleton and a surface layer (skin). The skeleton is made of laminated carbon fiber, making it light and strong. It supports the structure and houses internal components: energy storage in the thighs and torso; communication modules that allow the manikin to remotely communicate with the physiological model (ADAM also can be plugged into a power supply for continuous, non-remote communication); water storage, from which water is sent to the skin to enable sweating; and "lungs" that simulate breathing with exhalation of warm humid air. Through its joints, the skeleton also allows passage of wiring harnesses and sweat tubes, to enable communication with the skin.

The surface layer is composed of 126 individual segmented sections, each of which is a stand-alone unit of intricate design. Each section has several layers—an outer, low-porosity metal layer through which water is distributed for sweating; a high-porosity metal layer that distributes the water to the outer layer; and a carbon fiber structural backing, in

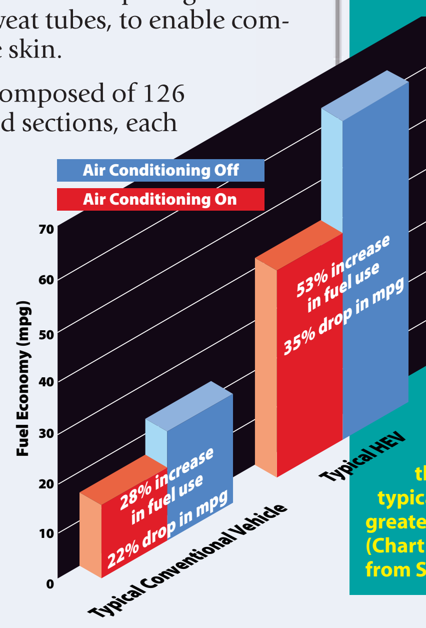
Driving Cool in Your HEV

So you finally bought an HEV—a model that emits about one-third the greenhouse gases and is rated at 63 mpg, nearly three times the gas mileage of a typical car. It's a comfortable, sleek car with snappy acceleration. And it's so quiet that you sometimes don't know that it's on.

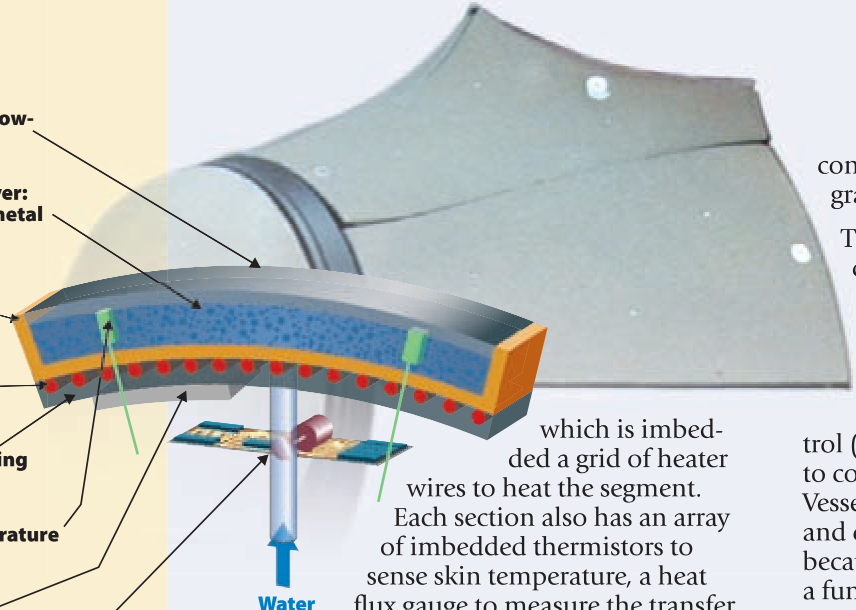
To take it on its inaugural spin, you get on the interstate, accelerate to an easily maintained speed of 70 mph, switch on the A/C, and cruise down the highway for 410 miles, at which point you exit the interstate to fill the gas tank. Then comes the surprise. You used 10 gallons of gasoline. That's only 41 miles per gallon! What gives?

The culprit is your A/C system. Your car's engine powers the same type of 4-kW, inefficient, vapor-compression A/C system powered by the average American car. The problem is, your HEV engine is a 1-liter, 70-hp engine, whereas typical sedan engines range from 2–3.5 liters and 160–250 hp. It takes about the same power to drive the A/C systems for both cars. But that power has a relatively higher impact on the smaller engine. So your car will experience a greater drop in gas mileage than will the typical, non-HEV vehicle. (Nonetheless, your HEV will still get more than twice the mileage than will the normal car driven with the A/C system on.)

What can be done? On your part, cut back on the use of the A/C when possible. In the long run, ADAM will play a part by testing and helping optimize the design of better ancillary systems to reduce the cooling load, including the design of more efficient A/C technologies. (See the sidebar "A Sound Idea for a Cool Car.")



Running the A/C has a relatively larger impact on a high-mileage HEV than it does on a more typical car. Still, the HEV will get greater absolute gas mileage. (Chart is based on test data taken from SC03 driving cycles.)



A three-dimensional detail of a surface segment shows its sophisticated construction and design, which enables it to sense and respond to heat and to control sweating.

which is imbedded a grid of heater wires to heat the segment. Each section also has an array of imbedded thermistors to sense skin temperature, a heat flux gauge to measure the transfer of heat between the backside surface and the internal body cavity of the manikin, and electronics to control the segment and to transmit data to and from the communication system.

Because of this segmentation, ADAM can cool or heat different sections of his body at different rates, depending on the environmental conditions to which parts of the body are exposed.

Central Control. Although ADAM is a sophisticated surface sensor that measures rates of heat loss in each zone, he does not respond on his own. Instead, he sends 120 sets of data on surface heat fluxes to the computer-based physiological-response model (120 sets because 6 of the 126 surface-layer segments are controlled in pairs). Using these data, the model predicts breathing rates, local skin temperatures, and sweat rates, and transmits the set points to ADAM. Based on the set points, ADAM adjusts his heating systems and sweat and breathing rates accordingly. Then, as ADAM interacts with the environment, he transmits the resultant changes in heat flux back to the model to continue the cycle.

The physiological-response model contains a detailed simulation of human internal physiological systems and thermoregulatory responses. The model consists of a human tissue system and a thermoregulatory system. The human tissue system represents the human body, including the physiological and thermal properties of the tissues—the bone, muscle, fat, and skin in arms, legs, and torso. It also includes the lung, abdominal, and brain tissues. The model calculates conduction heat transfer based on temperature gradients between tissue nodes.

The thermoregulatory system simulates the circulatory system and the respiratory system, the flow rates of these systems, and the heat transfer due to conduction within the fluids, mass transfer of fluid, and convective heat transfer to tissues. It also controls physiological response, such as vasomotor control (how nerves and muscles cause blood vessels to constrict or dilate), sweating, and shivering. Vessel constriction and dilation varies with skin and core temperatures and with each body zone because of vessel diameters. Sweating response is a function of skin and core temperatures and the number of sweat glands in each zone. Shivering is a function of skin and core temperatures and the amount of muscle in each zone. Blood flow is a function of skin and core temperatures and the metabolic rate.

The physiological-response model consists of about 40,000 nodes and elements. Because the model is so detailed, it presents a fairly complete picture of temperature distribution. As a result, it accurately simulates temperatures, heat transfers, and physiological responses to heat transfer. But it cannot by itself tell ADAM how comfortable he ought to feel. That part belongs to the thermal-comfort model.

Feelin' Good. By themselves, sensing and physiological responses have little value for designing systems to help passengers be comfortable in their cars. That responsibility falls to the therma-comfort model. This empirical model is based on work done at the University of California at Berkeley, in which human subjects were tested in transient and steady-state thermal conditions to determine their perceptions of local and overall thermal comfort. Using this testing data, the model predicts the local sensation of 19 body parts, the comfort of those parts, the overall sensation (given the input on local sensations), and the overall comfort. Plus, the model predicts how quickly a body or parts of the body will become comfortable under transient thermal conditions.

ADAM the manikin does not directly "talk" to the thermal-comfort model. Instead, the "conversation" is between the two models. The

A Sound Idea for a Cool Car

NREL engineers are working on an idea that could make good use of the waste heat from your car's exhaust system. They are researching a device that would use that heat to produce sound and then use the sound to cool your car—a concept known as thermoacoustic cooling.

Thermoacoustic effects have been understood for more than 100 years. However, only over the past two decades has substantial improvement been made to the design of thermoacoustic engines and refrigeration cycles. Recent thermoacoustic refrigerators have flown on the space shuttle and cooled electronics in a Navy destroyer. The idea is simple . . . the waste heat from your vehicle can be used to set up a temperature difference across a pile of plates or "stack." During periodic fluctuations in gas pressure, the gas passing through the stack is heated at the proper phase in the acoustic cycle to amplify the oscillations—much like light waves in an optical laser. The imperfect thermal contact in the stack's pores provides the phasing between compressions, expansions, and acoustic displacement necessary to lead the gas through the desired thermoacoustic cycle.

Furthermore, our thermoacoustic device pumps heat using standing sound waves to take the working fluid (helium) through a thermodynamic cycle. We rely on the heating and

physiological model sends sets of surface temperature data and core temperature data to the thermal comfort model, which uses that data to determine local and global sensations. It then uses the local and global sensations to determine the local and global comfort of ADAM the passenger.

A More Comfortable Car

Given this, we are now ready to dress ADAM, put him in a car, subject him to different environmental conditions, and test ancillary systems to see how effective they are in making him comfortable, while trying to save energy at the same time. Dressing him is important because the clothes he wears affect the transient thermal response.

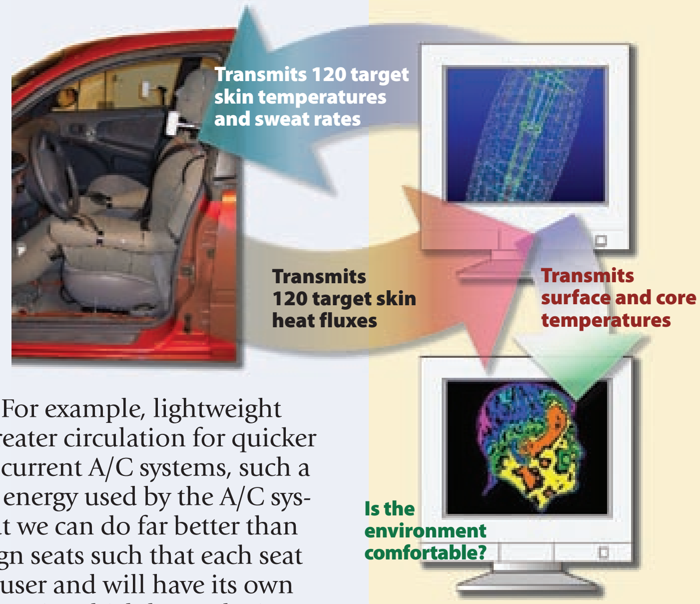
What kind of ancillary systems will our research help make possible in our next generation of cars because of ADAM? There are many. We can, for example, design better windshields and windows that will substantially reduce solar radiation entering the vehicle, while allowing visibility that is as good as typical windshields. Especially in hot, sunny climates, solar radiation will quickly heat a car and necessitate the use of substantial A/C energy to cool the car down. Advanced windshields and windows could also be designed with coatings that could quickly de-ice them in cold weather without having to rely on defrosters.

We could also design cars that are ventilated when parked, to dissipate heat when a car is left to soak in the sun. This would save A/C energy that may otherwise have to be used to cool the car from a high temperature.

A major improvement would be advanced A/C systems. Rather than rely on engine-driven vapor compression, we could use the heat from exhaust systems to cool our vehicles. There are several concepts being explored for this, including absorptive cooling (which uses an absorption refrigeration cycle rather than a vapor compression cycle), metal hydride cooling (in which the endothermic reaction—a reaction that pulls heat from the environment—of desorbing hydrogen from a metal hydride can cool the vehicle); or thermoacoustic cooling (in which waste heat is used to produce sound waves, which generate compression and expansion cycles to cool the vehicle—see sidebar "A Sound Idea for a Cool Car").

Something ostensibly as simple as seats can save significant energy while making you more comfortable. For example, lightweight mesh seats allow greater circulation for quicker cooling. Even with current A/C systems, such a seat can reduce the energy used by the A/C system by 3%–5%. But we can do far better than this. We could design seats such that each seat will conform to its user and will have its own individual A/C system in which low-velocity cool air circulates along your body on demand to cool you, without having to cool the entire car. Moreover, we could combine such a system with the use of new approaches in A/C systems, such as thermoacoustic cooling.

By using ADAM to test and prove such new concepts, we will be able to help the automotive industry incorporate a wide variety of advanced ancillary systems in our cars and light trucks. This could decrease our use of energy for ancillary systems by 75% or more. If we project that kind of reduction to a national level, our next generation of cars and trucks could reduce the nation's consumption of gasoline by 5 billion gallons per year, just for our A/C systems.



The three-part system: 1) ADAM the manikin, which senses temperature and sends data on heat flux to the 2) physiological-response model, which predicts the local skin temperatures and sweat rates, and transmits the set points to ADAM to control sweat and breathing rates, and 3) the thermal-comfort model, which determines the comfort of the manikin and its various segments based on surface and core temperature data received from the physiological model.

For More Information

Farrington, R.B.; Rugh, J.P.; Bharathan, D.; Burke, R. (2004). "Use of a Thermal Manikin to Evaluate Human Thermoregulatory Responses in Transient, Non-Uniform, Thermal Environments." SAE document number: 2004-01-2345. http://www.sae.org/servlets/ productDetail?PROD_TYP=PAPER&PROD_CD=2004-01-2345. Accessed December 30, 2004.

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Farrington, R. B.; Anderson, R.; Blake, D. M.; Burch, S. D.; Cuddy, M. R.; Keyser, M. A.; Rugh, J. P. (1999). "Challenges and Potential Solutions for Reducing Climate Control Loads in Conventional and Hybrid Electric Vehicles." 15 pp.; NREL Report No. CP-540-25975.

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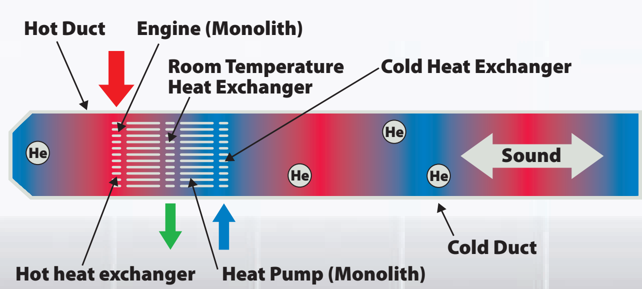
cooling that accompany the compression and expansion of a gas in a sound wave to produce the cooling for the interior of the vehicle.

This concept has many potential advantages over a conventional A/C system. It uses waste heat, is reliable and inexpensive, does not entail the use of an extra energy load on the engine, relies on gases that are environmentally benign, has no sliding parts (and thus should have a long lifetime), and requires no lubrication. The down side is, because of its low energy density, the device could take up a lot of volume. If we can overcome that barrier, it could be one of the cool technologies in your next-generation car.



In a thermoacoustic device, the heating and cooling that accompany the compression and expansion of a gas in a sound wave produces cooling for the interior of the vehicle.